The Effects of Space Radiation on Optocouplers*

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Abstract

Space radiation effects on optocouplers are discussed, including permanent degradation from protons and electrons, and short-duration transients from protons and heavy ions. Proton displacement damage is shown to be the most important degradation mechanism, even for optocouplers with radiation resistant light emitters. Amplifier design and light sensitivity both contribute to transient effects, which can persist for time periods of nearly one microsecond in some devices.

I. Introduction

Optocouplers are deceptively simple devices that have turned out to be very susceptible to radiation effects in space. Permanent damage occurred in one type of optocoupler on Topex-Poseidon (operating at 1330 km at high inclination) after about two years of operation [1]; and proton-induced transients in a different type of optocoupler caused partial shutdown of the Hubble space telescope (low altitude space shuttle orbit) after upgraded electronics were installed in 1997 [2]. Both situations were unexpected because older radiation test results had indicated that optocouplers were relatively immune to radiation damage. This is partly due to the lack of understanding about internal degradation mechanisms. For example, Figure 1 compares degradation of the 4N49 optocoupler used on Topex-Poseidon when it is irradiated with protons and gamma rays [3]. Note the extreme degradation that occurs in the proton environment. Older work using gamma rays had erroneously indicated that relatively minor degradation would occur from space radiation.

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Optocouplers are hybrid components with no explicit control of either the light emitting diode or photodetector/amplifier components other than overall performance of the entire assembly. Many optocouplers use lateral coupling, relying on "light pipes" formed from silicone to couple light from the LED to the photodetector, introducing yet another variable in their design. The physical properties of the coupling medium, emitter surface, and the photodetector all influence the amount of light that is coupled between the two components, in addition to the electrical properties of the components.

This paper discusses how space radiation affects optocouplers, comparing different optocoupler technologies. Permanent degradation effects and transient effects are included in the paper, as well as the effects of temperature and aging on overall performance. Hardness assurance and statistical considerations are also discussed.

II. Types of Optocouplers

There are two basic types of optocouplers: digital optocouplers, which simply use the LED output to activate a digital circuit or transistor switch; and linear optocouplers, which are intended for applications in linear amplifiers and power converters. Linear optocouplers are designed to maintain a very narrow range of current transfer ratio over a wide range of input currents compared with digital optocouplers. Linear optocouplers compensate for the substantial decrease in LED light output with temperature by operating the phototransistor at high injection, well beyond the peak in the β-I_C curve. Digital optocouplers are usually operated at low injection, resulting in a much stronger temperature dependence for CTR compared to linear optocouplers. These fundamental differences in design affect the radiation response and the interpretation of experimental results.

There are also reliability considerations. Unlike silicon devices, light-emitting diodes exhibit significant degradation in light output over relatively short time periods – 5-20% in 20,000 hours [4] – which must be taken into account along with degradation from radiation. Temperature is also a factor in their overall performance.

Examples of two different circuit configurations that are used for optocouplers are shown in Figure 2. The most basic type of optocoupler uses a simple phototransistor. This configuration can be used in a wide variety of applications, but is limited in response time because of the inherent limitations of the basic transistor amplifier. Other variations of this circuit are also used, including Darlington transistor configurations. Response time can be reduced by using a high speed comparator integrated along with the photodetector, as shown in the second basic circuit of Figure 2.

A wide range of light-emitting diodes can be used for optocouplers. Some LED technologies are extremely sensitive to displacement damage, while others are relatively immune to such problems. Many optocoupler manufacturers purchase the LEDs from outside suppliers, and have little knowledge or awareness of the fabrication technology. This introduces a large element of uncertainty in the radiation response, making it difficult to use older radiation data to assess the radiation vulnerability of optocouplers.

III. Permanent Degradation

A. LED Displacement Damage

The sensitivity of light-emitting diodes to displacement damage from protons varies widely for different LED technologies. The simplest type of LED is a homojunction device, formed by solution growth with liquid-phase epitaxy. AlGaAs LEDs (nominal wavelength 880 nm) have higher efficiency than GaAs devices that are fabricated with similar processes, and AlGaAs emitters are used in many types of optocouplers. It is also possible to use more complex processes to fabricate LEDs, creating a double-heterojunction (DH) structure [5]. The wavelength of DH LEDs can be adjusted over a wide range, from approximately 630 to 850 nm using different combinations of layers and materials; DH LEDs with 800 nm are widely available, and are used by some optocoupler manufacturers even though they are less efficient that 880 nm homojunction LEDs. One prominent manufacturer of optocouplers uses GaAsP DH LEDs (700 nm) in most products, but also uses 820 nm AlGaAs LEDs in some versions.

Figure 3 compares the response of two LED technologies from one manufacturer (twelve different units were tested of each type). The 800 nm LED exhibits far less damage than the 880 nm devices. However, two factors make this comparison more difficult to make. First, the 880 nm devices are more efficient, with initial light output that is about three times greater than that of the 800 nm devices. Second, there appears to be more variability in the radiation response of the 800 nm devices. When these factors are combined, the potential advantages of the shorter wavelength devices are less clear.

A further example of the variability in the radiation response of the 800 nm devices is shown in Figure 4 (the particular device shown is identical to that of the 800 nm devices in Figure 3, except for a larger total die area). In this case six different parts were tested. Five of the tested units show relatively consistent degradation, but the sixth has a very different response. The atypical unit has far more severe degradation than the 880 nm devices at low-to-moderate forward current, and essentially stops operating under those conditions. The underlying reasons for this type of response are unknown. There was no apparent difference in the initial electrical characteristics and light output efficiency of either of the worst units in Figures 3 and 4.

LED degradation also depends on operating current [3,6]. Figure 5 shows an example for a linear optocoupler which is dominated by LED degradation, although there are small contributions from the phototransistor and charge collection components. Before irradiation, the peak in the CTR current dependence occurs at about 0.5 mA. For input currents above 0.5 mA, the phototransistor is in the high injection mode, and the gain is actually higher for lower input current conditions. However, after irradiation the reduced light output of the LED decreases the operating current, effectively moving high current operation of the phototransistor to higher input currents.

This relationship between the current dependence of phototransistor gain and the LED degradation results in significantly less degradation at higher input currents at low fluences. However, as the radiation level increases, relatively more damage will occur at higher input currents because of the shift in operating conditions.

B. Phototransistor Degradation

Displacement damage also affects the phototransistor. There are two separate issues: first, collection of diffused photocurrent which depends on the minority carrier lifetime, diffusion length and optical absorption depth of the photodetector; and second, degradation of transistor gain. The former component will be important for all types of optocouplers, including those with high gain amplifiers, while the latter is only significant for optocouplers with simple phototransistors.

Figure 6 shows how these two components are affected by 50 MeV protons for a linear optocoupler with 880 nm wavelength. The photoresponse is the dominant mechanism under these operating conditions. The magnitude of the degradation depends on the underlying structure and the wavelength; it is significantly lower for optocouplers using 700 nm LEDs compared to those operating near 900 nm [3].

C. Ionization Damage

Although displacement damage produces far more damage than ionization effects, ionization damage is still an important factor. Figure 7 shows how ionization damage affects a digital optocoupler with a 700 nm LED that is relatively immune to displacement damage. Similar results for a different type of optocoupler were shown previously in Figure 1.

Ionization damage can also cause phototransistor leakage current to increase. Although leakage current is less important than the proton displacement damage issue, it can be still be a significant factor. Initial collector-emitter leakage currents are typically below 1 nA before irradiation, but in a larger population there are typically a small number of devices with much larger leakage current. At 50 krad(Si) leakage current can increase by as much as a factor of ten. This can cause difficulties in some applications because leakage current is strongly temperature dependent, doubling approximately every 10 °C. Thus, it is important to use phototransistors in circuits where significant increases in leakage current do not cause operational problems.

D. Lot Variability and Hardness Assurance

Lot variability is an important issue for optocouplers. Examples of variations in LED degradation within a lot were shown previously in Figures 3 and 4. The fact that some units within a lot can degrade much more than predicted from small test sample results is an important consideration when evaluating test results. The dominant problem is that of LED degradation, and more work needs to be done to understand why such variability is possible in these devices.

LED output is also affected by temperature, decreasing by about a factor of two at 75 °C compared to room temperature. Thus, maximum temperature is a worst-case condition for optocoupler degradation.

The gradual degradation of LED output during normal operation is also important (this problem is unique to LEDs, and does not occur in more conventional devices). LED degradation depends on operating conditions and temperature. Typical degradation is 5-20% over a five-year time period, depending on technology and operating conditions.

Another important factor in hardness assurance is the physical coupling between the LED and photodetector. This is particularly important for optocouplers with lateral coupling. Voids and bubbles can occur in the silicone coupling material that affect the CTR [3], along with the physical properties -- edge roughness and efficiency -- of the LED, as well as the physical orientation of the LED and photodetector. Figure 8 shows the initial distribution of CTR for a digital optocoupler before radiation degradation and temperature are taken into account. Because of the wide range of initial CTR values, radiation test data have a much higher probability of overestimating the radiation hardness compared to more conventional components.

IV. Transient Responses

A. *Basic Issues*

Heavy ions (or protons) strike devices at random locations, causing a continuous distribution of charges at critical internal nodes. This in turn causes the output transients from a radiation test (or from a space application) to vary in amplitude and duration, depending on where the incoming particle struck the device. Thus, there is some ambiguity in defining the effect of a given particle type (and energy) on an electronic circuit. The magnitude and duration of the transient may also depend on the loading conditions.

For some types of optocouplers, single-event transients are dominated by charge collected within the large-area photodiode, which tends to produce a well defined pulse characteristic for most of the transients. However, this is not the case for optocouplers with high-gain amplifiers. Consequently, it is necessary to evaluate these devices statistically, with a distribution of pulse widths and amplitudes.

B. *Protons*

As shown by LaBel, et al., protons can produce transients in optocouplers with high-gain amplifiers, but not in more basic types of optocouplers [2]. Their experiments showed output durations up to 70 ns. The cross section that they observed with 62 MeV protons was approximately 5×10^{-8} cm^2; the photodiode area of the devices that they studied was about 1.1×10^{-3} cm^2. As discussed in the introduction, proton transients were identified as the cause of malfunctions of the Hubble space telescope when it passed through the south Atlantic anomaly.

LaBel et al. also noted an unusual angular dependence when they used different incident angles for their laboratory experiments. The cross section was unaffected by angle until relatively large angles were used. At 80°, the cross section started to increase; it continued to increase up to 90°, with a maximum value about six times greater than the cross section at angles below 80°. They were not entirely successful in explaining these results, primarily because they assumed a very shallow charge collection volume that would predict a much larger increase in cross section at extreme angles than they actually observed.

C. *Heavy Ions*

Pulse widths are also produced when optocouplers are irradiated with heavy ions. Because of the long range, it is more straightforward to determine the internal mechanisms that cause transients when heavy ions are used compared with similar tests with protons. Tests with heavy ions showed that although charge produced from ions striking the photodiode was an important factor, the high-gain amplifier also made a significant contribution to the cross section [7]. Figure 9 shows the cross section of a device with the same design as that used in the proton transient tests of reference 2. Note that the threshold LET is very low -- less than 0.3 MeV-cm^2/mg. Note in addition that the cross section quickly increases to a value well above that of the physical area of the photodiode.

Much wider pulses were produced when these optocouplers were irradiated with heavy ions compared to the results with protons. For LET values above 3 MeV-cm^2/mg the output was fully saturated (at 5 V with a 2 mA load condition), persisting for 150 ns. Above 10 MeV-cm^2/mg even longer pulse widths occurred, occasionally exceeding 500 ns. Experiments with the amplifier section shielded were used to separate the photodiode and amplifier contributions to the cross section.

Charge collection measurements were made with heavy ions as well as with laboratory alpha particle sources. Those measurements showed that the charge collection depth of the optocouplers was about 50 µm, much more than that usually assumed for transient responses of integrated circuits. Those results were used to show that the angle dependence observed during proton tests was caused by a superposition of direct ionization from protons along with the response of the short range proton recoil product. The detailed behavior at high angles was due to the geometry of the photodiode, which has an aspect ratio of about 0.1 when the charge collection depth is properly accounted for.

V. Circuit and System Applications

A. Digital Applications

Extensive derating is necessary in order to assure reliable operation of optocouplers in space environments [8]. Low input currents are often used in applications because of the LED wearout mechanism, which is less severe at low currents. However, this operates the optocoupler at low current where proton degradation is more severe. LED degradation from protons can be reduced by selecting optocouplers that use DH LEDs with less sensitivity to proton displacement damage. Although this reduces the degradation, one must still deal with the issue of statistical variability, as discussed earlier. Displacement damage in the phototransistor remains important, even for devices with radiation-tolerant LEDs.

As noted earlier, high-speed optocouplers are susceptible to transients which can be of relatively long duration. The cross section for such transients is high because of the large-area photodiode. The transient problem can be accommodated by normal circuit and system design approaches, providing it is recognized as an important mechanism. It is also important to avoid applications of optocouplers in asynchronous applications (such as overload signals in power systems) where transients can produce false resets that can cause temporary system malfunctions.

B. Linear Applications

Optocouplers are frequently used in power converters, providing isolation between the transformer-coupled output and the regulation stage. Although transients are unimportant in this type of design, CTR degradation is a critical problem. Figure 10 shows the results of proton tests of power converters under different load conditions. Once the optocoupler degrades past the minimum CTR, the circuit no longer regulates properly and the output begins to increase. Because of the particular circuit design, the minimum CTR is actually higher under lightly loaded conditions.

The results in Figure 10 are essentially subsystem tests, which do not provide specific information about how the optocouplers degrade. They must be derated to account for temperature effects, LED wearout and device variability. Howver, they demonstrate how optocoupler degradation can cause circuit failures at very low radiation levels.

VI. Conclusions

This paper has separated permanent degradation of optocouplers into three different components: LED degradation, which is heavily dependent on the particular LED technology used in the design; and degradation of light collection efficiency and phototransistor gain. The results show that optocoupler degradation is often dominated by displacement damage from protons, and identifies ways to select LED technologies that are less sensitive to permanent damage in space.

Transients from protons and heavy ions were also discussed. Transients are clearly more important for optocouplers with integrated high-gain amplifiers than for more basic optocouplers with simple transistor gain stages. Heavy ions can produce transients with relatively long duration, and this type of response must be taken into account when they are used in space applications.

Finally, one must always be aware that optocouplers are very simple hybrid devices that can easily be modified for a variety of output devices. There are no explicit controls on the LED technology that is used. Extreme care must be taken in evaluating radiation effects on these devices, in using archival data, and in attempting to extend data on a particular device type to other devices made by the same manufacturer.

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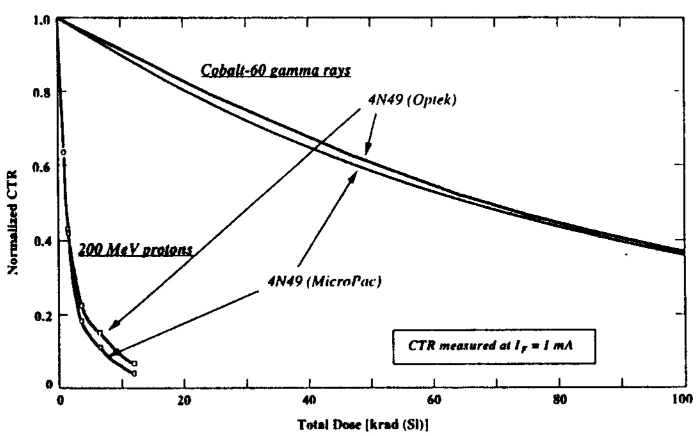

Figure 1. Degradation of the 4N49 optocoupler from protons and gamma rays

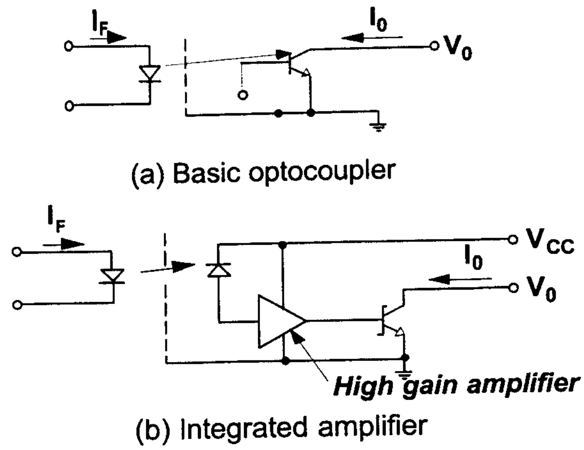

Figure 2. Examples of different circuit configurations used for optocouplers.

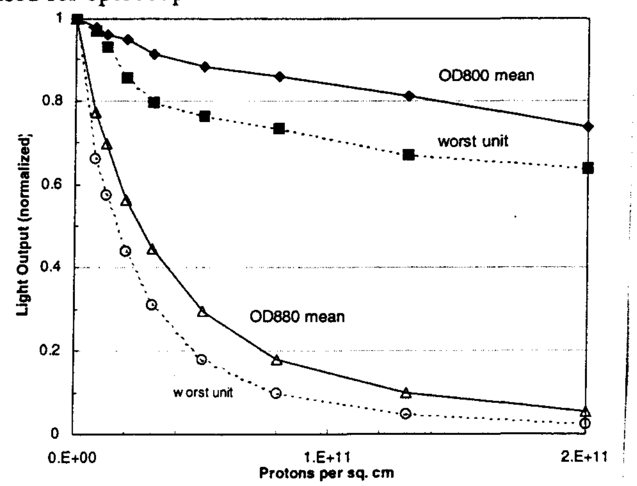

Figure 3. Comparison of the degradation of two different LED technologies after irradiation with 50 MeV protons.

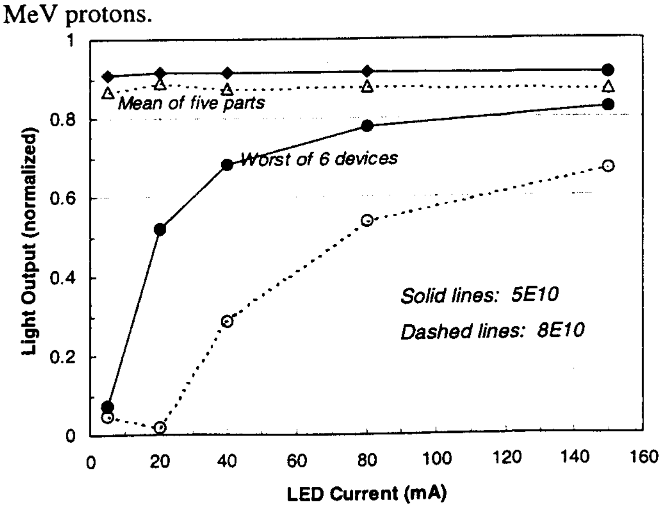

Figure 4. Proton degradation of 800 nm LEDs showing extreme degradation of one unit in a small test sample.

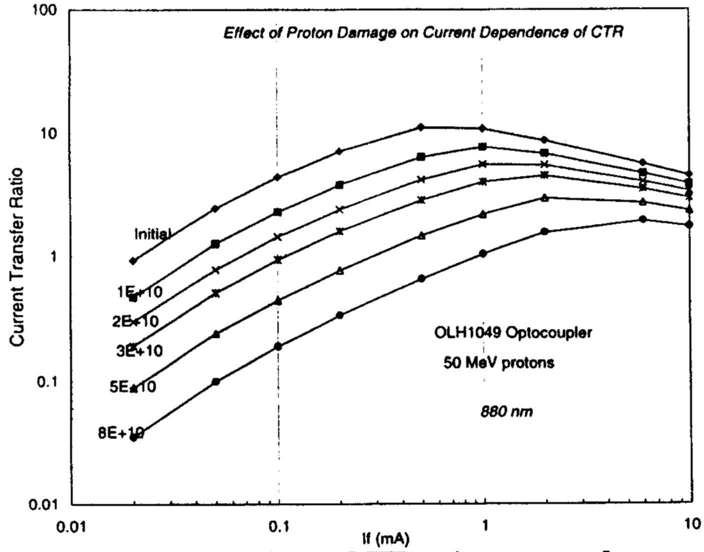

Figure 5. Dependence of CTR on input current for a linear optocoupler with an 880 nm LED.

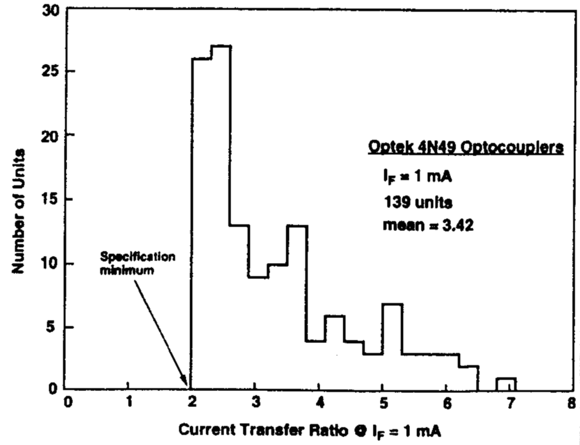

Figure 8. Distribution of CTR values for optocouplers from two different manufacturers.

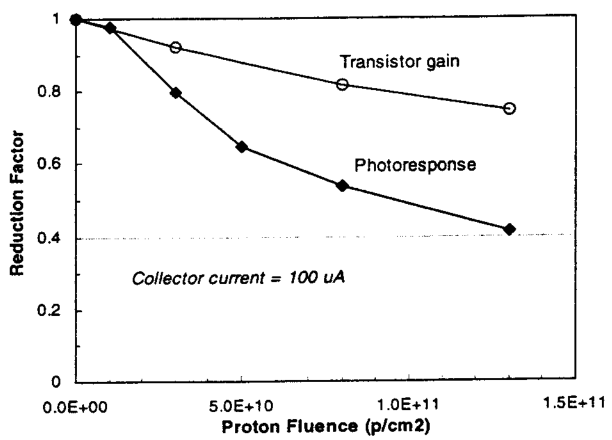

Figure 6. Effects of proton irradiation on photoresponse and gain degradation for a linear optocoupler operating at a wavelength of 880 nm.

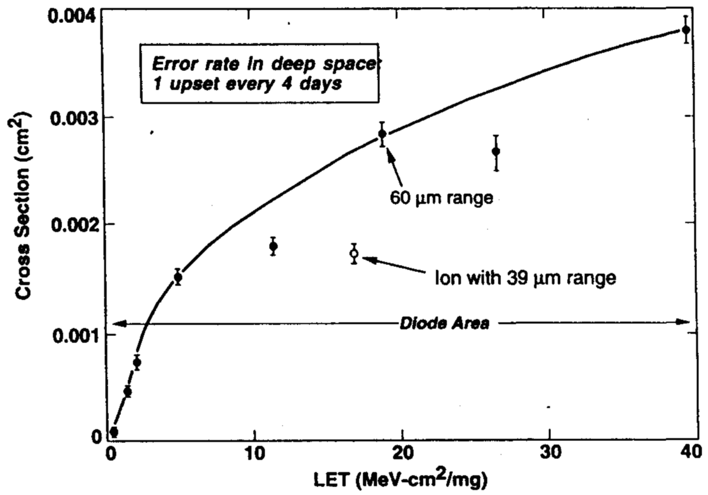

Figure 9. Cross section of the Hewlett-Packard 5203 optical coupler when irradiated with heavy ions.

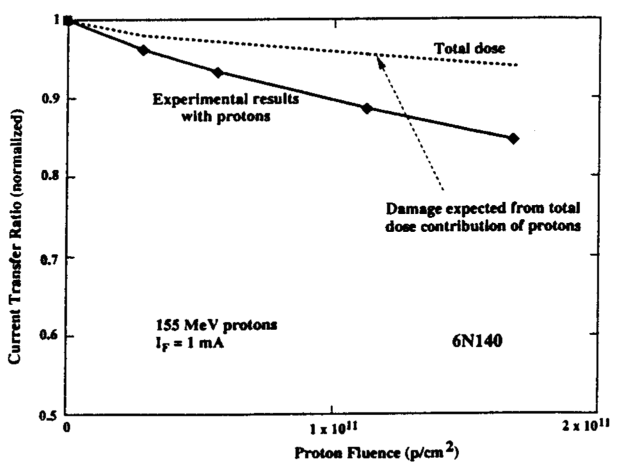

Figure 7. Effect of ionization damage on the CTR of an optocoupler operating at 700 nm.

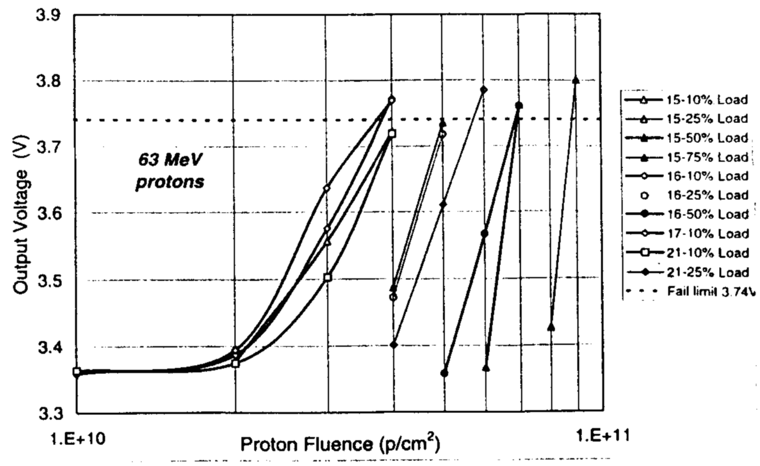

Figure 10. The effect of protons on power converters that use linear optocouplers for coupling between the output and regulator stage.

Viewgraphs for Presentation on Space Radiation Effects in Optocouplers

1 - Outline

Optocoupler technologies

Permanent Degradation

- Proton Damage Effects in LEDs
- Proton Damage in Detectors and Phototransistors

Transient Effects

- Protons
- Heavy Ions

Applications

- Digital Applications
- Analog Applications

Conclusions

2 - Figure 1 from paper (Degradation of 4N49 optocoupler from protons and gamma rays)

3 - Figure 2 from paper (Examples of different circuit configurations used for optocouplers)

4 - Light Emitting Diode Technologies

AlGaAs Homojunctions

- 880 nm
- Diffused structure
- Very high efficiency

Double Heterojunction LEDs

- Wide range of wavelengths
- More complex fabrication sequence
- Lower efficiency

5 - Figure 3 from paper (Comparison of the degradation of two different LED technologies after irradiation with 50 MeV protons

6 - Figure 4 from paper (Proton degradation of 800 nm LEDs showing extreme degradation of one unit in a small test sample)

7 - Figure 5 from paper (Dependence of CTR on input current for a linear optocoupler with an 880 nm LED

8 - Figure 6 from paper (Effects of proton irradiation on photoresponse and gain degradation for a linear optocoupler operating at 880 nm)

9 - Figure 7 from paper (Effect of ionization damage on the CTR of an optocoupler operating at 700 nm)

10 - Figure 8 from paper (Distribution of CTR values for optocouplers)

11 - Transients from Protons

Short Duration Transients Produced

- Only significant for optocouplers with high-gain amplifiers
- Maximum transient duration ~ 70 ns

Unusual Angle Dependence

- Cross section increases for incident angles above 80 degrees
- Appears inconsistent with charge collection assumptions

12 - Figure 9 from paper (Cross section of the Hewlett-Packard 5203 optical coupler when irradiated with heavy ions

13 - Heavy Ion Results

Transients Have Much Longer Duration

- Up to 500 ns
- Photodiode and amplifier both contribute to cross section
- Based on experiments with partial shield

Charge Collection Depth

- Determined by calculation and alpha particle measurements
- Approximately 50 microns
- Explains proton angle dependence

14 - Figure 10 from paper (The effect of protons on power converters that use linear optocouplers for coupling between the output and regulator stage)

15 - Selection of Optocoupler Technologies for Space

AlGaAs LEDs Highly Sensitive to Displacement Damage

- Select other technologies if possible
- Avoid operation at low forward currens

Displacement Damage in Photodiode and Amplifier

- Limit performance of optocouplers in space
- Wavelength dependent

Transients Must Be Accounted for in Applications

- Proton-induced transients very important for earth orbits
- Heavy ion transients also significant
    - Longer duration
    - Approximately two upset per week in deep space or GEO orbits

16 - Conclusions

Optocouplers Are Potentially Very Susceptible to Space Radiation

Displacement Damage Is Critical for Some LED Technologies

- Tests with gamma radiation ineffective
- LED technology and operating current determine sensitivity

Transients Are Also Important

- Caused upsets on Hubble space telescope
- Longer duration transients occur with heavy ions
- Optocouplers with high gain amplifiers are the most sensitive

Careful Selection of Technology Required for Successful Use of Optocouplers in Space

- Many types of LEDs are used
- Not well controlled
- Fundamental mechanisms not well understood
- Archival data can be misleading